Octupole Correlations in Excited Bands of Superdeformed ^{152}Dy

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Abstract

RPA calculations, based on the cranked shell model, are performed for superdeformed ^{152}Dy in which five excited bands have been found recently. We show that characteristic features of the observed dynamical moments of inertia are well accounted for by explicitly taking the octupole correlations into account. Importance of the interplay between rotation and octupole vibrations is stressed, and it is suggested that one of the observed excited bands might be a collective octupole vibration built on the superdeformed yrast band.

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The discovery of superdeformed (SD) rotational bands has opened many new avenues in studies of nuclear structure at the extremes of rapid rotation and large deformation. Recent experimental developments, especially large γ-ray detector arrays (Eurogam, Gammasphere, Ga.Sp, etc.), have offered better observational limits which help in clarifying many aspects of high-spin nuclear structure.

Recently, five excited SD bands (Bands $2-6$) have been observed in ^{152}Dy in a Eurogam experiment [1]. According to various theoretical calculations [2–4], ^{152}Dy has a SD doubly-closed-shell configuration corresponding to the large single-particle gaps at Z=66 and N=86. Since the pairing correlations in SD bands in the A=150 region are expected to be seriously quenched due to the low level-density of single-particle states and rapid rotation, the angular momentum variations in the dynamical moments of inertia, $\mathcal{J}^{(2)} = dI/d\omega$, are mainly due to the intrinsic angular momentum alignment of single-particle orbitals, especially high-N intruder orbitals [2–4]. Consequently, the $\mathcal{J}^{(2)}$ moments of inertia carry important experimental information about single-particle configurations in SD bands.

The excited SD bands in ^{152}Dy, observed by Dagnall et al. [1], have a very low intensity relative to the yrast SD band. This might be related to the predicted SD magic structure in ^{152}Dy. Due to its magic structure, collective excitation modes are expected to influence the properties of near-yrast SD bands in ^{152}Dy. In this context, octupole vibrations play a very special role. According to the RPA calculations based on the cranked shell model [5,6], low-lying octupole vibrations are more important than low-lying quadrupole vibrations built on the SD shape. Strong octupole correlations in SD states have also been suggested theoretically in Refs. [7–15]. The calculations of Ref. [16] demonstrate that the inclusion of the coupling between quasiparticle and octupole vibrational modes is important for understanding the experimental data for SD ^{193}Hg [10].

In this Letter, we discuss octupole correlations in excited SD bands of ^{152}Dy. Comparing our results with the experimental data, we propose a plausible scenario for the microscopic structure of excited SD bands in ^{152}Dy. This scenario is compatible with the discussions by Dagnall et al. [1] but the influence of octupole correlations is explicitly considered. Indeed, one of the excited SD bands is suggested to have a collective octupole vibrational character. If this interpretation is correct, this is the first case in which the collective vibrational mode at SD high-spin states has been observed experimentally.[1]

In order to investigate the influence of octupole vibrations on the excitation spectrum of SD ^{152}Dy, the RPA treatment has been carried out. The model Hamiltonian has been assumed to be of the form:

$$H = h'_{\text{s.p.}} - \frac{1}{2}\sum_K \chi_{3K} Q''^\dagger_{3K} Q''_{3K} - \frac{1}{2}\sum_K \chi_{1K}(\tau_3 D_{1K})''^\dagger (\tau_3 D_{1K})'' \,, \tag{1}$$

where $h'_{\text{s.p.}}$ is a cranked single-particle Nilsson Hamiltonian, $h'_{\text{s.p.}} = h_{\text{Nilsson}} - \omega_{\text{rot}}\hat{J}_x$, and $Q''_{3K} = (r^3 Y_{3K})''$ and $D''_{1K} = (rY_{1K})''$ are, respectively, the doubly stretched octupole and dipole operators defined by coordinates $x''_i = \frac{\omega_i}{\omega_0}x_i$ [18]. The equilibrium quadrupole deformations have been determined by means of the shell correction method. A large configuration

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[1]Recently, an excited band in SD ^{190}Hg has been interpreted in terms of octupole vibrations [17].

space composed of nine major shells for both protons and neutrons has been used for solving the coupled RPA dispersion equations. The spurious velocity dependence associated with the l^2 and $\vec{l} \cdot \vec{s}$ terms in the Nilsson potential are removed by means of the method proposed in Ref. [19]. We note that the obtained single-particle routhians are similar to those for the Woods-Saxon potential [3]. The pairing gaps Δ_p and Δ_n are assumed to be zero: Although dynamical pairing fluctuations never vanish, *relative* energy spectra and *relative* alignments are known to be well described by the simple cranked shell-model routhians without pairing at $\omega_{\rm rot} \geq 0.3\,{\rm MeV}/\hbar$, i.e., in the region where the experimental data are available [20,21]. In order to determine the isoscalar coupling strengths, χ_{3K}, we have carried out the systematic RPA calculations for the low-frequency $I^\pi = 3^-$ states in medium-heavy nuclei. Guided by these calculations, we use $\chi_{3K} = 1.05\chi_{3K}^{\rm HO}$ where $\chi_{3K}^{\rm HO}$ are the selfconsistent values for the harmonic oscillator potential [18]. For the isovector dipole coupling strengths we use $\chi_{1K} = -\pi V_1/\langle (r^2)'' \rangle$ with $V_1 = 140\,{\rm MeV}$ [22].

Figure 1(a) shows the RPA eigenvalues as functions of rotational frequency $\omega_{\rm rot}$. The lowest excitation mode with signature $\alpha = 1$ (dotted line) can be associated with the collective octupole vibrational band. The band has $K = 0$ at $\omega_{\rm rot} = 0$, but the K-mixing due to the Coriolis force is significant at high rotational frequencies. The B(E3)-values calculated at $\omega_{\rm rot} = 0$ in the strong coupling scheme are around B(E3; $3^- \to 0^+) \approx 35$ W.u. By comparing Fig. 1(b) and (c), we see that the octupole collectivity carried by the lowest $\alpha = 1$ band decreases gradually with $\omega_{\rm rot}$. On the other hand, collectivity of the lowest excitation mode with $\alpha = 0$ (solid line) is weak and this mode has a dominant 1p-1h configuration at high frequency. Excitation energy of this band drastically decreases in the high-frequency region and its alignment, $i = -\frac{dE_x}{d\omega}$, is evaluated to be about $5\hbar$. Since this band has much lower excitation energy at high frequency than the octupole vibrational $\alpha = 1$ band, it may be populated with higher intensity.

Calculations show that the neutron N=86 single-particle shell gap persists at high frequencies, while the proton Z=66 shell gap vanishes at high angular momenta where the proton $N = 7$ ($\alpha = -1/2$) orbital crosses the fourth $N = 6$ ($\alpha = -1/2$) orbital (see Fig. 2 and discussion in Ref. [1]). The 1p-1h excitation associated with these two orbitals gives rise to the lowest excited state with signature $\alpha = 0$. The alignment of this 1p-1h excitation is equal to $i_{\rm p} - i_{\rm h} \approx 4.5\hbar$; i.e., the large alignment of the band comes from the intrinsic angular momentum of the proton intruder $N = 7$ orbital. In contrast, the lowest 1p-1h excitation with $\alpha = 1$ is associated with the proton $N = 7$ ($\alpha = -1/2$) and the third $N = 6$ ($\alpha = 1/2$) orbital. Its excitation energy is about 1 MeV higher than that of the $\alpha = 0$ band in the highest frequency region. Because of this effective energy gap, the collective mode with $\alpha = 1$ survives up to rather high frequencies. Since the alignment of the collective octupole phonon is less than $3\hbar$, the lowest $\alpha = 0$ band carries a larger alignment and becomes lower at high frequency.

In the following, we discuss the dynamical moments of inertia of Bands 2, 3, and 6 for which octupole correlations are calculated to be important. Characteristic features of Bands 2, 3, and 6, determined in Ref. [1], can be summarized as follows: (i) $\mathcal{J}^{(2)}$ of Band 2 (Band 3) has a bump (dip) at $\omega_{\rm rot} \approx 0.5 {\rm MeV}/\hbar$; (ii) Bands 2 and 3 are populated with higher intensity compared to other excited bands (Bands $4-6$); (iii) $\mathcal{J}^{(2)}$ of Band 6 is larger than that of the SD yrast band and is almost constant as a function of rotational frequency; (iv) At low values of $\omega_{\rm rot}$ Band 6 shows a decay branch into the yrast SD band.

On the basis of the above observations, we propose a scenario in which the lowest and the second lowest excited $\alpha = 0$ states (solid lines in Fig. 1), and the lowest $\alpha = 1$ state (dotted line) correspond to Bands 2, 3, and 6, respectively. Firstly, the $\mathcal{J}^{(2)}$ bump in Band 2 and the dip of Band 3 occurring at the same frequency can be associated with crossing between the two lowest $\alpha = 0$ states, see Fig. 1. Secondly, the high intensity of Bands 2 and 3 indicates that at high frequency these bands have lower excitation energy than the other bands. Our conjecture is consistent with the intensity data for Band 2.[2] Thirdly, weak ω_{rot}-dependence of $\mathcal{J}^{(2)}$ in Band 6 suggests an almost constant curvature $\frac{d^2 E_x}{d\omega^2}$ of the routhian (see eq. (2)). Finally, the partial decay of Band 6 into the yrast SD band indicates that Band 6 may be a collective band possessing significant (E1) transition matrix elements into the yrast SD band.

In order to make the comparison with experimental data quantitative, we calculate the dynamical moments of inertia $\mathcal{J}^{(2)}$. They can be decomposed as

$$\mathcal{J}^{(2)} = \mathcal{J}_0^{(2)} + \frac{di}{d\omega} = \mathcal{J}_0^{(2)} - \frac{d^2 E_x}{d\omega^2} \; , \tag{2}$$

where $\mathcal{J}_0^{(2)}$ denotes the dynamical moment of inertia of the yrast SD band of ^{152}Dy (RPA vacuum). We approximate the experimental $\mathcal{J}_0^{(2)}$ by the Harris expansion, $\mathcal{J}_0^{(2)} = \alpha + \beta \omega^2$, with $\alpha = 88.5 \hbar^2 \mathrm{MeV}^{-1}$ and $\beta = -11.9 \hbar^4 \mathrm{MeV}^{-3}$. Calculated and experimental values of $\mathcal{J}^{(2)}$ are compared in Fig. 3; it is seen that the characteristic features of the experimental data are well reproduced. It is worth noting that the octupole correlations are also important for reproducing experimental $\mathcal{J}^{(2)}$ values for Bands 2 and 3.

In order to discuss the collectivity of octupole correlations, we show in Fig. 4 the forward RPA amplitudes[3] $\psi_n(\alpha\beta)$ for Bands 2, 3, and 6. We see that Bands 2 and 3 correspond to simple 1p-1h excitations at the highest frequency region; i.e., proton $N = 6 \to N = 7$ and proton $N = 6 \to N = 5$ excitations, respectively. Bands 2 and 3 cross at $\omega_{\mathrm{rot}}^{(c)} \approx 0.5$ MeV/$\hbar$. For $\omega_{\mathrm{rot}} < \omega_{\mathrm{rot}}^{(c)}$, collective components in both bands are significant. In fact, the interaction matrix element between Bands 2 and 3 would be too small to reproduce the observed bumps and dips of $\mathcal{J}^{(2)}$ if octupole correlations were turned off. On the other hand, Band 6 has vibrational character in the whole range of rotational frequency. The octupole collectivity of this band decreases with rotational frequency.

In summary, we have investigated the effects of octupole correlations in excited SD bands of ^{152}Dy by means of the RPA based on the cranked shell model. We found that a low-lying octupole vibrational band ($\alpha = 1$) appears near the yrast band ($E_x \approx 1$ MeV). According to our scenario, Bands 2, 3, and 6 have negative parity. Band 2 (3) is the lowest (second lowest) $\alpha = 0$ band. Band 6 is the octupole vibrational $\alpha = 1$ band. The collectivity of Band 6 is expected to gradually decrease with ω_{rot}, while Bands 2 and 3 cross each other at $\omega_{\mathrm{rot}} \approx 0.5$ MeV/$\hbar$. The calculated $\mathcal{J}^{(2)}$ values reflect the ω_{rot}-dependence of the

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[2] On the other hand, calculations suggest that intensity of Band 3 should be weaker than that of Band 2 whereas experimentally it is similar; this weakens our interpretation of Band 3.

[3] Sums of the squared backward RPA amplitudes, $\sum_{\alpha\beta} |\varphi_n(\alpha\beta)|^2$, at $\omega_{\mathrm{rot}} = 0.3$MeV/$\hbar$ are 0.13, 0.11 and 0.48 for Bands 2, 3 and 6, respectively.

internal structures of these bands, and seem to agree well with major characteristics found experimentally.

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FIGURES

FIG. 1. Results of RPA calculations at quadrupole deformation $\delta_{\mathrm{osc}} = 0.59$. (a) Calculated RPA eigenvalues (in MeV) for SD ^{152}Dy, plotted as functions of rotational frequency ω_{rot} (in MeV/$\hbar$). Solid (dotted) lines indicate negative-parity states with signature $\alpha = 0$ ($\alpha = 1$). The lowest $\alpha = 1$ state has $K = 0$ in the limit $\omega_{\mathrm{rot}} = 0$. (b) Electric octupole strength $\sum_K |\langle n|\frac{1}{2}(1 + \tau_3)Q_{3K}|0\rangle|^2$ at $\omega_{\mathrm{rot}} = 0.3$MeV/$\hbar$ in Weisskopf units ($|0\rangle$ and $|n\rangle$ denote the RPA ground state and excited states, respectively). Solid and dotted lines indicate the $\alpha = 0$ and $\alpha = 1$ states, respectively. The vertical axis represents the excitation energy as in (a). (c) The same as (b), except for $\omega_{\mathrm{rot}} = 0.6$ MeV/$\hbar$.

FIG. 2. Neutron and proton single-particle routhians as functions of rotational frequency ω_{rot}. The Nilsson parameters (κ, μ) are adopted from ref. [23], and the spurious velocity dependence associated with l^2 and $\vec{l}\cdot\vec{s}$ terms are removed according to a prescription developed by Kinouchi and Kishimoto [19]. Orbitals having parity and signature, $(\pi, \alpha) = (+, 1/2), (+, -1/2), (-, 1/2)$, and $(-, -1/2)$ are shown by solid, dashed, dotted, and dash-dotted lines, respectively. The oscillator quantum number, N_{osc}, is indicated for "high-N" orbitals.

FIG. 3. Calculated (solid lines) and experimental (symbols) dynamical moments of inertia for excited SD bands (Bands 2, 3, and 6) in ^{152}Dy. Dotted lines indicate $\mathcal{J}^{(2)}$ for the yrast SD band, which is approximated by the Harris formula $\mathcal{J}_0^{(2)} = \alpha + \beta\omega^2$ with $\alpha = 88.5\hbar^2$MeV^{-1} and $\beta = -11.9\hbar^4$MeV^{-3}. See text for details.

FIG. 4. Absolute values of the forward amplitudes, $|\psi_n(\alpha\beta)|$, of the lowest and the second lowest RPA solutions in the $\alpha = 0$ sector (portions a and b), and the lowest RPA solution in the $\alpha = 1$ sector (portion c), corresponding to Bands 2, 3, and 6, respectively. Solid (Dashed) lines indicate neutron (proton) amplitudes. All amplitudes whose absolute values are greater than 1.5×10^{-1} are displayed. The characteristic p-h excitations are indicated.

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